Evaluation of MODIS thermal IR band L1B radiances during SAFARI 2000

Christopher C. Moeller,[1] Henry E. Revercomb,[1] Steven A. Ackerman,[1] W. Paul Menzel,[2] and Robert O. Knuteson[1]

Received 15 March 2002; revised 27 June 2002; accepted 14 August 2002; published 3 April 2003.

[1] On 11 September 2000, a NASA ER-2 aircraft underflew the Terra spacecraft during the Southern Africa Regional Science Initiative (SAFARI) 2000 field experiment. The Scanning High Resolution Interferometer Sounder (S-HIS), Moderate Resolution Imaging Spectroradiometer (MODIS) Airborne Simulator (MAS), and Cloud Physics Lidar (CPL) instruments onboard the ER-2 have provided a data set for a first look at the accuracy of the Collect 3 (L1B Version 3.X) Terra MODIS L1B radiances for the thermal infrared (TIR) bands. Based on comparisons between MODIS and S-HIS nadir viewing data and an estimation of the existing uncertainties, the radiances of most MODIS TIR bands are found to be very near or within specification. There does not appear to be a significant influence by electronic cross talk on the midwave IR (MWIR) bands for the low reflectance, flat thermal scenes used in the evaluation. Longwave IR (LWIR) split window band residuals are within 0.1 K with an estimated uncertainty of ±0.13 K, raising confidence in their accuracy. Midtropospheric water vapor band residuals are also within specification, despite known detector striping in these bands. Residuals in the LWIR upper tropospheric CO_2 bands 34–36 exceed specification. However, these are not considered strong indications of L1B performance issues due to possible undocumented uncertainty in the altitude correction for the unmeasured atmosphere above the ER-2 aircraft level. *INDEX TERMS:* 1694 Global Change: Instruments and techniques; 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques; 4294 Oceanography: General: Instruments and techniques; *KEYWORDS:* Terra, MODIS, calibration, thermal, SAFARI, ER-2

Citation: Moeller, C. C., H. E. Revercomb, S. A. Ackerman, W. P. Menzel, and R. O. Knuteson, Evaluation of MODIS thermal IR band L1B radiances during SAFARI 2000, *J. Geophys. Res.*, *108*(D13), 8494, doi:10.1029/2002JD002323, 2003.

1. Introduction

[2] One of several primary objectives of the Southern Africa Regional Science Initiative (SAFARI) 2000 field campaign (17 August to 25 September 2000) was to collect data for assessing the accuracy of science products, including L1B radiance, from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on the Terra satellite. Terra was launched into a Sun synchronous 1030 am local time (LT) descending orbit on 18 December 1999 to begin a new era of global climate and climate change studies. MODIS, the cornerstone instrument of Terra, provides daily global coverage in its 36 reflectance and thermal infrared (TIR) spectral bands at 1 km resolution or better (Table 1). A daily complement of 44 science products is created from the MODIS L1B radiances to monitor the geophysical signatures of global climate and climate change. Many of these products are critically reliant upon accurate TIR band radiances (e.g., Sea Surface Temperature (SST), Cloud Masking, Cloud Top Properties, Atmospheric Profiles, Land Surface Temperature, etc.) over the climatic regimes of the global domain. MODIS has a 1% (at typical radiance) prelaunch accuracy specification for most of its midwave IR (MWIR) (3–5 μm) and longwave IR (LWIR) (6–15 μm) bands (0.75% for the MWIR 3.7 μm window band; 0.5% for the LWIR 11 and 12 μm split window bands; 10% for MWIR 3.9 μm fire band).

[3] During SAFARI 2000, the MODIS product assessment data collection objective was met by flying a NASA ER-2 over southern Africa and offshore waters [*King et al.*, 2003], typically coordinated with the morning Terra overpass. Eighteen successful ER-2 flights were made. The ER-2 is an effective platform for assessing L1B of on-orbit radiometric instruments because of its large payload capacity (1300 kg) and ability to fly above about 95% of the Earth's atmosphere, closely simulating spaceborne measurements. The MODIS Airborne Simulator (MAS) [*King et al.*, 1996], Scanning High Resolution Interferometer Sounder (S-HIS) [*Revercomb et al.*, 1998], and Cloud Physics Lidar (CPL) [*McGill et al.*, 2002] data from these ER-2 flights is useful for direct comparisons to on-orbit MODIS radiometric data. MAS contains 19 spectral bands

[1]Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin-Madison, Madison, Wisconsin, USA.

[2]National Oceanic and Atmospheric Administration (NOAA)/National Environmental Satellite Data and Information Service (NESDIS)/Office of Research and Applications (ORA), University of Wisconsin-Madison, Madison, Wisconsin, USA.

Copyright 2003 by the American Geophysical Union.
0148-0227/03/2002JD002323$09.00

Table 1. MODIS Spectral and Radiometric Characteristics[a]

MODIS TIR Band Number	CWL (Bandwidth) (μm)	Radiometric Accuracy Specification[b]	MAS Equivalent Band Number	CWL (Bandwidth) (μm)	Primary Use
20	3.788 (3.70–3.88)	0.75% (0.18 K)	30	3.770 (3.70–3.85)	Surface/Cloud Temperature
21	3.992 (3.96–4.04)	10.0% (3.0 K)	31	3.940 (3.86–4.02)	Fire detection
22	3.971 (3.93–4.02)	1.0% (0.25 K)	31	3.940 (3.86 4.02)	Surface/Cloud Temperature
23	4.057 (4.01–4.10)	1.0% (0.25 K)	32	4.095 (4.01–4.18)	Surface/Cloud Temperature
24	4.473(4.43–4.52)	1.0% (0.19 K)	35	4.550 (4.47–4.63)	Atmospheric Temperature
25	4.545 (4.50–4.59)	1.0% (0.24 K)	35	4.550 (4.47–4.63)	Atmospheric Temperature
26	1.382 (1.36–1.40)	Reflectance Band	–	–	Cirrus Detection
27	6.765 (6.64–6.89)	1.0% (0.27 K)	40	5.315 (5.22–5.37)	Water Vapor
28	7.337 (7.17–7.50)	1.0% (0.32 K)	40	5.315 (5.22–5.37)	Water Vapor
29	8.524 (8.34–8.71)	1.0% (0.53 K)	42	8.564 (8.33–8.76)	Water Vapor, Cloud
30	9.730 (9.58–9.88)	1.0% (0.42 K)	43	9.665 (9.44–9.93)	Ozone
31	11.014 (10.76–11.27)	0.5% (0.34 K)	45	10.943 (10.69–11.21)	Surface/Cloud Temperature
32	12.018 (11.78–12.27)	0.5% (0.37 K)	46	11.954 (11.68–12.21)	Surface/Cloud Temperature
33	13.361 (13.21–13.51)	1.0% (0.61 K)	48	13.193(12.94–13.45)	Cloud Top Properties
34	13.679 (13.52–13.84)	1.0% (0.58 K)	49	13.712(13.43–14.04)	Cloud Top Properties
35	13.911 (13.74–14.08)	1.0% (0.55 K)	49	13.712 (13.43–14.04)	Cloud Top Properties
36	14.194 (14.06–14.33)	1.0% (0.47 K)	50	14.193 (13.95–14.40)	Cloud Top Properties

[a]MODIS has TIR bands in the MWIR (bands 20–25) and LWIR (bands 27–36) spectral regions. MODIS reflectance bands 1–19 not shown.
[b]For typical Earth scene radiance of that band.

(11 in the TIR) at high spatial resolution (50 m) that closely simulate MODIS spectral bands (see Table 1). S-HIS 0.5 cm^{-1} resolution spectra (3–18 μm) provide better than 0.5 K radiometric accuracy with 2 km spatial resolution. Both instruments are operable as cross track scanners (MAS 37 km swath, S-HIS 30 km swath from the nominal ER-2 altitude of 20 km). Together MAS and S-HIS form a powerful calibration assessment tandem with MAS capturing spatial influences and S-HIS capturing spectral influences in the data scenes. The CPL is used as an effective discriminator of thin cloud in data scenes, to eliminate data scenes with transient obstructions from the data sample.

[4] The accuracy of the MODIS L1B TIR band radiances will be evaluated in this paper in the context of the prelaunch accuracy specification. The evaluation will be based upon comparisons between MODIS and clear-sky S-HIS data scenes (as confirmed by MAS and CPL) collected during a mission over the Benguela Current off the west coast of Namibia on 11 September 2000. In the first look perspective of this evaluation, the MODIS radiances are averaged over all 10 detectors of each MODIS 1 km TIR band, and over both sides of the MODIS scene mirror; the MODIS data were processed using Version 3.0.0.6 (Collect 3) at the Goddard Space Flight Center Distributed Active Archive Center (GSFC DAAC), the latest version available at the time of the data analysis. In this version, influences on TIR bands such as optical cross talk into the LWIR bands and scene mirror reflectance dependence on angle of incidence of upwelling radiance [*Godden*, 1999; *Barnes et al.*, 1998; *Guenther et al.*, 1998] are corrected using the most recent coefficient estimates.

2. Data Set

[5] The procedure for assessing MODIS calibration using the ER-2 is in principal relatively simple. It includes instrumenting the ER-2 for radiometric measurements similar to those of MODIS, planning ER-2 flights so that the aircraft instruments map a small portion of the coincident MODIS swath in a viewing geometry closely resembling that of MODIS (Figure 1), and processing MODIS comparisons so that spatial, spectral, altitude and geometric (i.e., view angle) dependencies are removed or minimized. As is depicted in Figure 1, a distinct advantage of using the ER-2 is that its instruments (MAS and S-HIS) collect down-looking measurements from above in much the same physical manner that MODIS measurements are collected. In this way, the spectral and spatial variation of the Earth–atmosphere temperature and emissivity are characterized over several thousand km^2 in 10 min of flight time. The burden of accuracy is thus largely placed on the integrated ER-2-based instrument observations rather than on the ability of in situ point or volume measurements to accu-

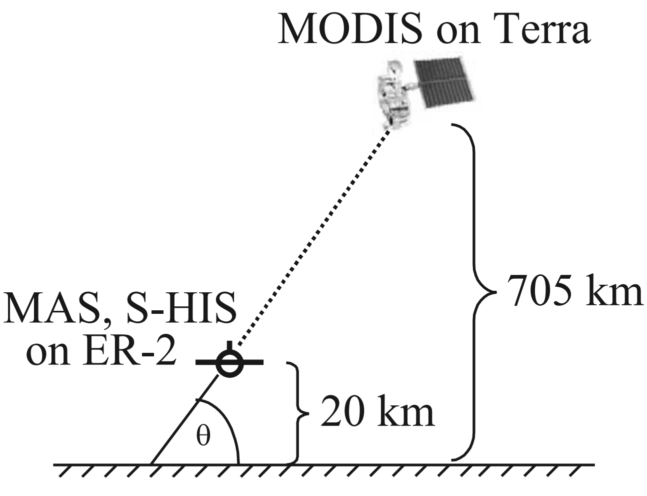

Figure 1. Example of matched ER-2 and MODIS slant paths for MODIS comparisons to MAS and S-HIS. The MAS and S-HIS on the ER-2 view the same Earth location as MODIS through the same slant path. The altitude difference between the ER-2 and the Terra must be removed to convert a MODIS simulated radiance at ER-2 level to spacecraft level. For the data used in this paper, MODIS and ER-2 both viewed common Earth locations at nadir (i.e., the ER-2 directly underneath Terra) but with a 7–18 min offset between the observations by the platforms (see Figure 2).

rately characterize the surface and atmospheric domain. The ER-2-based observations provide a snapshot at a moment in time of the existing conditions; however, in the absence of clouds over deep ocean scenes, the characterization is usually representative of conditions over a larger time interval. For example, MAS repeat coverage in the Gulf of Mexico has shown that 11 μm brightness temperature change over a 30 min interval is <0.1 K [*Moeller et al.*, 2001]. This reference is provided as evidence that temporal variability of deep water ocean TIR band radiances is very small for a modest time interval. While it is always desirable to confirm temporal variability by repeating an ER-2 flight line, the myriad of objectives for the lengthy flight plan of 11 September 2000 did not include repeat coverage to verify the expected small temporal variability.

[6] While the ER-2 flies above about 95% of the atmosphere from its nominal 20 km cruising altitude, the 5% above the aircraft is not measured by the onboard instruments. Thus, for those MODIS spectral bands that sense atmospheric emission in that 5%, it is necessary to characterize the temperature and mixing ratio of the absorbing gases (primarily CO_2 and O_3) and apply a model-based correction (referred to as an "altitude correction" hereforth). Radiosondes report temperature to about 10 hPa, covering some portion of this 5%, however the bulk of the stratosphere can be represented either by standard atmosphere databases or in opportune occurrences by the Upper Atmosphere Research Satellites (UARS) Halogen Occultation Experiment (HALOE) instrument soundings [*Russell et al.*, 1994]. As will be seen in section 3, the sensitivity of the altitude correction to the choice of atmospheric characterization is small for most bands but important for LWIR ozone and CO_2 sensitive bands.

[7] During SAFARI 2000, the NASA ER-2 routinely underflew the Terra satellite to collect data for direct assessment of MODIS L1B and L2 science products [*King et al.*, 2003]. While the large majority of ER-2 flights covered land scenes or partly cloudy water scenes, on 11 September 2000, ER-2 flight 00-160 was positioned directly on the Terra orbital track (i.e., nadir) in cloud-free skies offshore of the coast of Namibia some 7–18 min prior to the Terra overpass at 0942 UTC (Figure 2). These offshore waters are characterized by the uniformly cool northbound Benguela Current, influencing a several hundred kilometer wide cross section off the coastline extending from Cape Town, South Africa in the south to near northern Namibia where it turns seaward with the coastal profile. This region often contains persistent marine stratocumulus clouds during the Austral late winter season, but on 11 September, a zone of clear skies was present in a region of dry low level offshore flow from southern Namibia. MAS and S-HIS data collected from 0924 to 0936 UTC covered a broad clear-sky region, which appears to have remained clear through the Terra overpass (Figure 2). The relatively flat thermal nature of the ocean scenes reduces sensitivity to colocation uncertainty between the MODIS and the ER-2-based observations.

[8] In addition to the ER-2-based observations, radiosonde data was collected for 11 September 2000 for a station at St. Helena Island (World Meteorological Organization (WMO) station 61901) in the South Atlantic (15°56′S, 5°04′W, elevation 435 m) some 2000 km to the west. The radiosonde data was used in the Line-by-line radiative transfer model (LBLRTM) [*Clough and Iacono*, 1995] with the Hitran96/JPL-extended database to correct for the altitude difference between MODIS and the ER-2 observations. The basic seven molecular species (H_2O, CO_2, O_3, N_2O, CO, CH_4, and O_2) were specified as absorbing gases in the LBLRTM model. H_2O (from radiosonde) and CO_2 (360 ppm) concentration were expressly specified; other absorbing gas concentrations were allowed to default to standard atmosphere concentrations with the exception of O_3 in the stratosphere (see discussion of HALOE retrievals just below). The St. Helena Island radiosonde was chosen because of its near sea level elevation (435 m), providing better lower atmosphere coverage for the radiative transfer model than radiosondes over the southwest African continent (typically launched from elevations of more than 1000 m). Temperature, water vapor, and ozone retrievals from HALOE were used to extend the atmospheric profile up to 100 km altitude. The spatial and temporal sampling of the HALOE instrument is sparse. The closest date for a near proximity HALOE retrieval was 1 September 2000, some 10 days before the ER-2 and Terra data collection. While this is clearly not optimal, the HALOE temperature, moisture, and ozone retrieval was accepted to characterize the upper atmosphere (above 26 km, 22 hPa). To test the sensitivity of the altitude correction to the atmospheric characterization, a second radiosonde at Windhoek, Namibia (WMO station 68110, 22°34′S, 17°06′E, elevation 1728 m) was collected to characterize the troposphere, and a seasonally and latitudinally interpolated standard atmosphere (temperature, moisture, ozone) was appended to characterize the stratosphere. Windhoek lies about 600 km east of the ER-2 data collection region, on the plateau of southern Africa some 200 km inland from the Namibian coast. These atmospheric characterizations are shown in Figure 3. The Windhoek profile is considerably drier (total precipitable water (TPW) = 8.1 mm) than that at St. Helena Island (TPW = 21.5 mm). Most of the additional water vapor in the St. Helena Island profile is contained in a moist, well mixed boundary layer. As will be seen later in Table 3, the radiative transfer model-based altitude correction is small (<0.1 K) for many MODIS bands (LWIR CO_2 bands excepted) and shows limited sensitivity to the atmospheric characterizations tested (Table 2).

3. Data Processing

[9] The MODIS L1B evaluation presented herein is based on selecting a region of clear-sky S-HIS observations for simulating MODIS observations, and comparing the ensemble averaged simulated radiances within the region to the ensemble averaged MODIS observed radiances within that same region. The simulated MODIS radiances are limited to S-HIS footprints with viewing geometry equivalent to that of the coincident MODIS observations (i.e., nadir scenes on 11 September 2000). For the cloud-free scenes selected for 11 September 2000 this translated to a MODIS data region of about 130 data lines along track by two to three MODIS 1 km footprints across track, centered on nadir (287 total footprints). The MODIS across track data region is approximately represented by the thickness of the ER-2 flight line in Figure 2 and ran from 0924:18 to 0934:56 UTC (S-HIS equivalent time) in the along track direction. There were

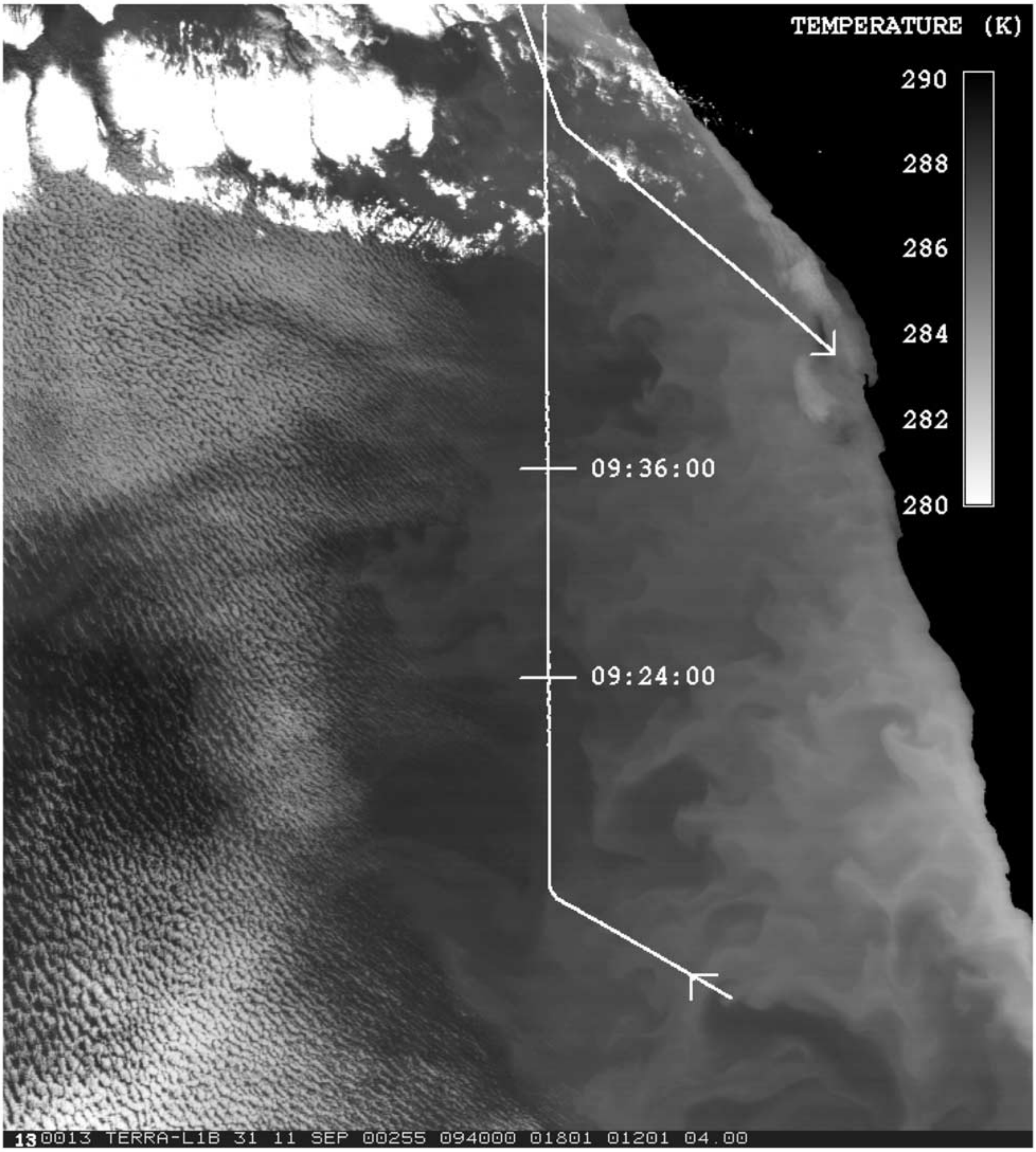

Figure 2. MODIS 11 μm imagery on 11 September 2000 for data collected between 0941 and 0943 UTC. A portion of the NASA ER-2 flight on 11 September is shown, including a south-to-north leg (solid line) along the Terra orbital track collecting nadir view S-HIS, MAS, and CPL data to facilitate comparisons with the MODIS L1B radiances. Nadir data from 0924:18 to 0934:56 UTC were used for comparisons to MODIS. These data are shown later in Figure 4. The Terra satellite overpass occurred at about 0942 UTC, 7–18 min after the ER-2 transect. The width of the time position markers is the approximate cross track coverage of the MAS 37 km swath. Time quantity on image given as HH:MM:SS.

869 S-HIS 2 km footprints in the data region (more because consecutive S-HIS footprint overlap is >80%).

[10] To simulate MODIS observations, spatial, spectral, temporal and altitude dependencies between MODIS and S-HIS were considered. The spatial dependence was rigorously evaluated by convolving the MODIS 1 km footprint, as given by the MODIS prelaunch spatial weighting function [*Barnes et al.*, 1998], and the S-HIS 2 km footprint

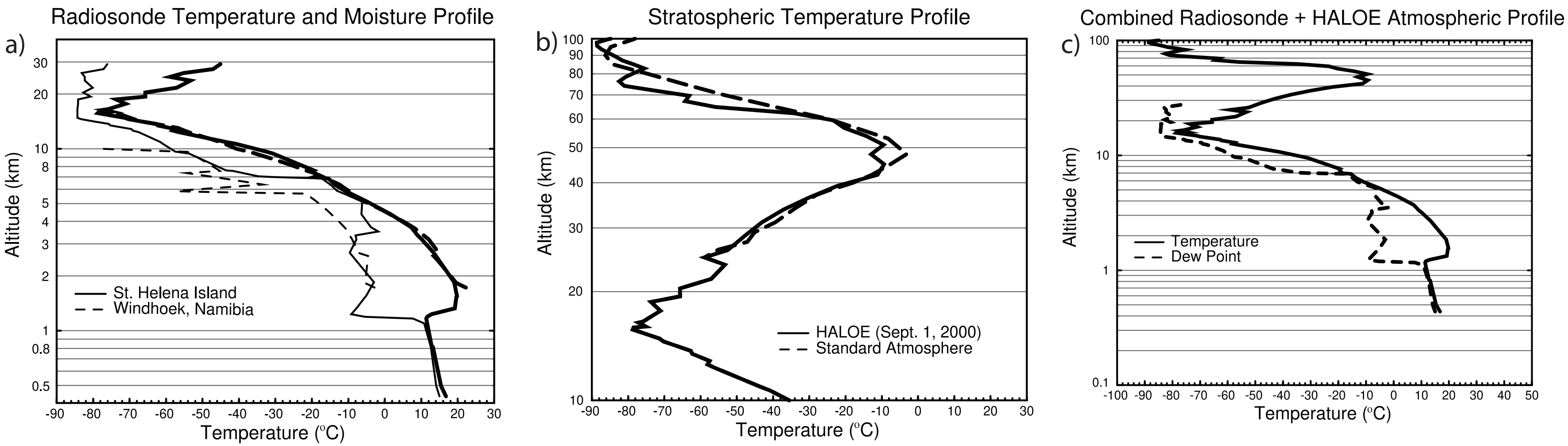

Figure 3. Tropospheric (left) and stratospheric (center) characterization tested in the radiative transfer model to correct for the atmosphere above the ER-2 (i.e., the altitude correction) on 11 September 2000. Radiosondes at St. Helena Island (61901) and Windhoek, Namibia (68110) were reviewed. St. Helena Island was chosen because of its vertical coverage and the prevalence of winds from the west through a large layer of the troposphere (not shown). The stratospheric characterization (beginning about 26 km altitude) was provided by the HALOE instrument. However, due to the large time difference (10 days) between the HALOE observations (1 September) and the ER-2 flight (11 September), a standard atmosphere stratospheric profile interpolated for the month of September at the latitude of 20°S was also generated for testing. The combinations of the St. Helena Island radiosonde with the HALOE retrieval, St. Helena Island radiosonde with an interpolated standard atmosphere, and Windhoek, Namibia radiosonde with the interpolated standard atmosphere were all tested to gain insight on the altitude correction sensitivity to atmospheric characterization (see section 3 and Table 2). The complete profile chosen for the altitude correction is shown at right.

Table 2. Estimated Uncertainties Associated With Various Components of the MODIS L1B Evaluation on 11 September 2000[a]

MODIS Band Number	Center Wavelength (μm)	Spatial Footprint Influence	Temporal Influence on Observations (up to 18 min)	Atmospheric Influence on Altitude Correction	S-HIS Linear Calibration Accuracy	RSS of All Uncertainties
20	3.788	0.06	<0.1	0.00	0.09	0.15
21	3.992	0.02	<0.1	0.00	0.08	0.13
22	3.971	0.02	<0.1	0.01	0.08	0.13
23	4.057	0.02	<0.1	0.00	0.08	0.13
24	4.473	0.01	<0.1	−0.08	0.09	0.16
25	4.545	0.01	<0.1	−0.01	0.07	0.12
27	6.765	−0.06	<0.1	−0.03	0.12	0.17
28	7.337	−0.06	<0.1	0.02	0.08	0.14
29	8.524	−0.03	<0.1	−0.02	0.08	0.13
30	9.730	0.00	<0.1	−0.65	0.07	0.66
31	11.014	−0.02	<0.1	0.00	0.08	0.13
32	12.018	−0.03	<0.1	−0.01	0.08	0.13
33	13.361	−0.01	<0.1	−0.07	0.08	0.15
34	13.679	0.03	<0.1	−0.12	0.08	0.18
35	13.911	0.03	<0.1	−0.26	0.11	0.30
36	14.194	0.05	<0.1	−0.31	0.16	0.37

[a]The spatial influence is estimated using MAS data convolved with the MODIS 1 km and S-HIS 2 km footprints. The temporal influence is an estimate of the scene temperature change in each band over the 7–18 min difference between the S-HIS and the MODIS observations. The altitude uncertainty is defined as the difference in the altitude correction caused by using different atmospheric profiles in the LBLRTM. S-HIS accuracy uncertainty is based on blackbody cavity component performance for the scene temperatures of 11 September. All quantities are in K, except as noted. The RSS uses 0.1 K to represent the temporal uncertainty contribution to the RSS.

over the MAS 50 m spatial resolution data. For the relatively flat thermal field of the clear-sky ocean scenes on 11 September 2000, the spatial dependence was found to be <0.1 K for all TIR bands (Table 2). The data region used in this test is the same as that for the MODIS L1B radiance evaluation. Thus, comparing the S-HIS 2 km footprint radiances directly to the MODIS 1 km footprint radiances was deemed acceptable in this L1B evaluation.

[11] The spectral dependence was treated by convolving the in-band (defined as spectral coverage from wavelength λ_1 (1% response) through peak response to λ_2 (1% response)) MODIS relative spectral response (RSR) over the S-HIS high resolution spectra. This removes the spectral dependence of atmospheric water vapor, CO_2, and other absorbing constituents, as well as surface emissivity from the results. MODIS TIR band RSR were carefully measured during prelaunch in a thermal vacuum environment (bands 20–28) and clean room environment (bands 29–36) with atmospheric correction [*Barnes et al.*, 1998]. RSR was measured for each detector of each MODIS band and is applied by detector in the MODIS L1B product algorithm [*Guenther et al.*, 1998], all versions to date through V3.X. For simulating MODIS radiances with S-HIS, the detector dependent RSR were used and later the simulated radiances for all footprints within the data region were averaged by band (i.e., detector independent). The detector to detector simulated brightness temperatures differed by <0.1 K for most bands (20–23 and 28–35), and <0.5 K for all other TIR bands. Inaccuracies in the MODIS RSR contribute to the difference between the MODIS simulations and observations of each band.

[12] As previously mentioned, MAS and S-HIS on the ER-2 overflew the data region from 0924:18 to 0934:56 UTC, 7 (northern end) to 18 (southern end) min before the MODIS 0942 UTC overpass on Terra. The MAS imagery was inspected for cloud contamination over the data region, with none being found. The CPL backscatter data showed a thin aged smoke layer between two and four km altitude. The radiometric impact of the smoke layer on the S-HIS and MODIS radiances is undocumented, but expected to be small (<0.5 K). Importantly, since the smoke layer was likely very similar during the ER-2 overflight and the Terra overpass 7–18 min later, its radiometric influence is integrated into both the S-HIS and MODIS observations. Figure 4 shows an along track profile of the MAS and S-HIS 11 μm brightness temperatures through the data region, as well as the colocated MODIS brightness temperatures collected 7–18 min later. Visual inspection of the data profiles reveals very similar structure among the different sensors over the entire data region. This suggests that MODIS and S-HIS viewed the same or very nearly the same cloud-free surface and atmospheric emission in their respective overpasses. S-HIS, MAS, and MODIS CO_2 sensitive band 35 data (not shown) was also reviewed and showed no clear evidence of temporal dependence. Based on previous experience [i.e., *Moeller et al.*, 2001] and the evidence of Figure 4, any uncertainty associated with the temporal difference between the S-HIS and MODIS observations on 11 September 2000 is estimated to be small (<0.1 K) in Table 2. It is noteworthy however that the temporal influence uncertainty provided in Table 2 does not include possible undetected Sun glint influence in the MWIR bands.

[13] With geometric, spatial, temporal and spectral considerations addressed, the difference or residual between MODIS observations (ob) and simulations (sim) for band i is given by:

$$\mathrm{Residual_i} = \mathrm{MODIS_{ob,705\ km,i}} - \left(\mathrm{MODIS_{sim,S-HIS,20\ km,i}} + \mathrm{Altitude\_correction_i}\right) \quad (1)$$

$\mathrm{MODIS_{ob,705km,i}}$ is the ensemble average of the 287 MODIS L1B radiance observations for all detectors and both scene mirror sides and $\mathrm{MODIS_{sim,S\text{-}HIS,20km,i}}$ is the simulated MODIS radiances from the 869 S-HIS radiance spectra over the 0924:18 to 0934:56 UTC duration, also averaged over all detectors and mirror sides. While detector and mirror side

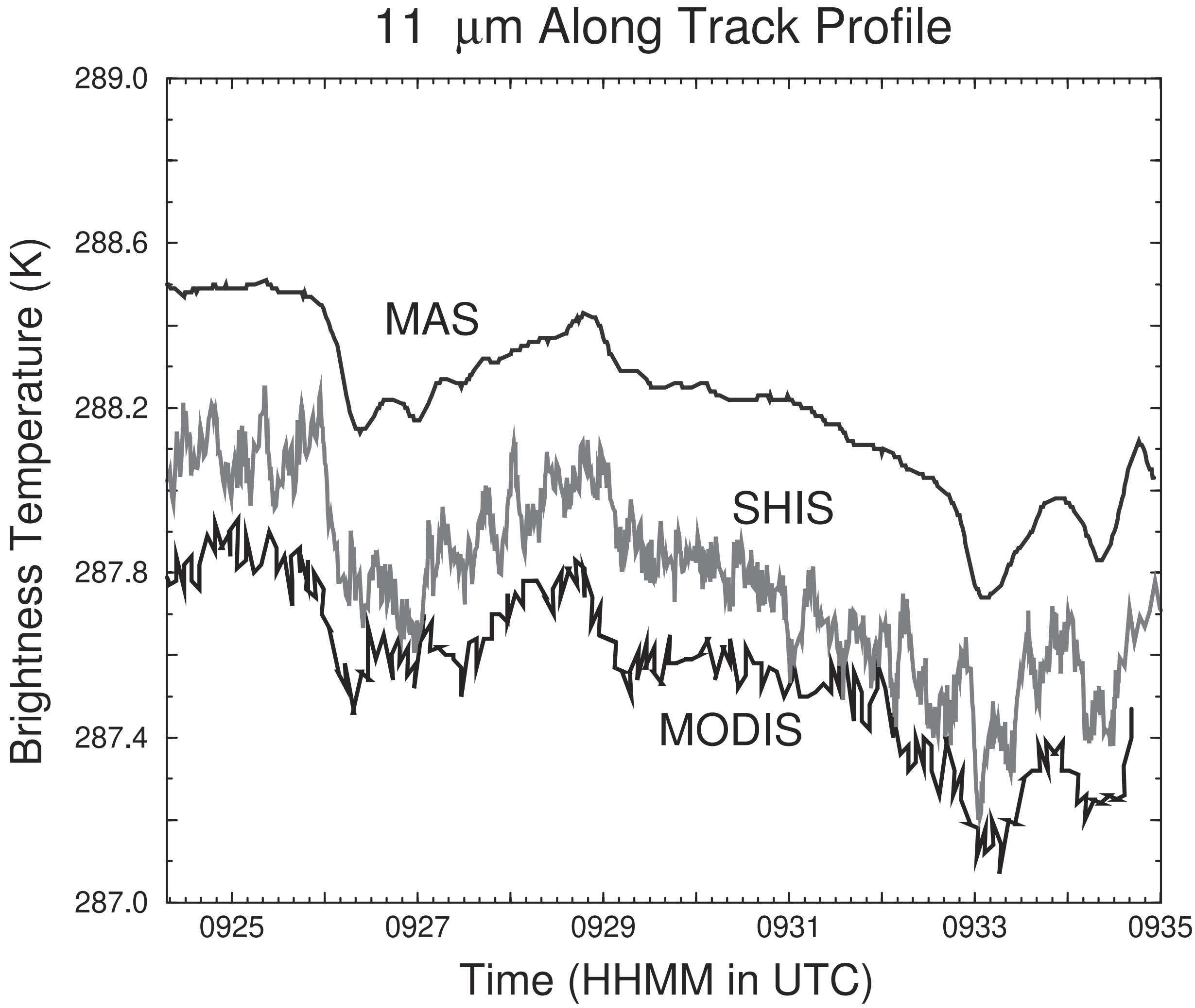

Figure 4. MAS and S-HIS 11 μm brightness temperature along track profiles from 0924:18 to 0934:56 UTC on 11 September 2000. MODIS 11 μm brightness temperature data collected at about 0942 UTC were colocated spatially with the MAS and S-HIS data using Earth geolocation and then assigned the appropriate ER-2 aircraft data time for plotting in this figure. The MAS 50 m spatial resolution data have been averaged over the S-HIS 2 km footprint. The S-HIS high spectral resolution data were convolved with the MODIS band 31 (11 μm) spectral data and then smoothed using a 10-data point moving window average to reduce the noise for plotting purposes. The plot shows very similar temperature structure between MODIS and ER-2-based observations, suggesting that atmospheric and surface emission over the 7–18 min time difference between MODIS and ER-2-based observations was very nearly constant. There are obvious brightness temperature offsets between MAS, S-HIS, and MODIS data in this figure. The MODIS residuals presented in this paper are based on the S-HIS and MODIS data example presented in this figure, averaged over all footprints, and then modified by the altitude correction.

striping is known to exist in MODIS data, it is not expressly evaluated in the first look perspective of this paper. A positive (negative) residual in (1) indicates that the MODIS calibrated brightness temperature is too warm (cold).

[14] The altitude correction for each band, i.e., the correction to adjust a 20 km level simulated MODIS radiance up to 705 km, is given by:

$$\text{Altitude\_correction}_i = \text{MODIS}_{\text{sim,raob,705 km},i} - \text{MODIS}_{\text{sim,raob,20 km},i} \qquad (2)$$

$\text{MODIS}_{\text{sim,raob,705 km},i}$ and $\text{MODIS}_{\text{sim,raob,20 km},i}$ are LBLRTM model radiances based on the 11 September 2000, 1200 UTC St. Helena Island radiosonde profile combined with the 1 September 2000 HALOE atmospheric profile data (Figure 3). To evaluate the influence of atmospheric characterization on the altitude correction, two additional atmospheric characterizations were used in the LBLRTM model. These were the St. Helena Island radiosonde with an interpolated (month of September and latitude of 20°S) standard atmosphere stratospheric profile, and a 11 September 2000, 1200 UTC radiosonde at Windhoek, Namibia combined with the interpolated stan-

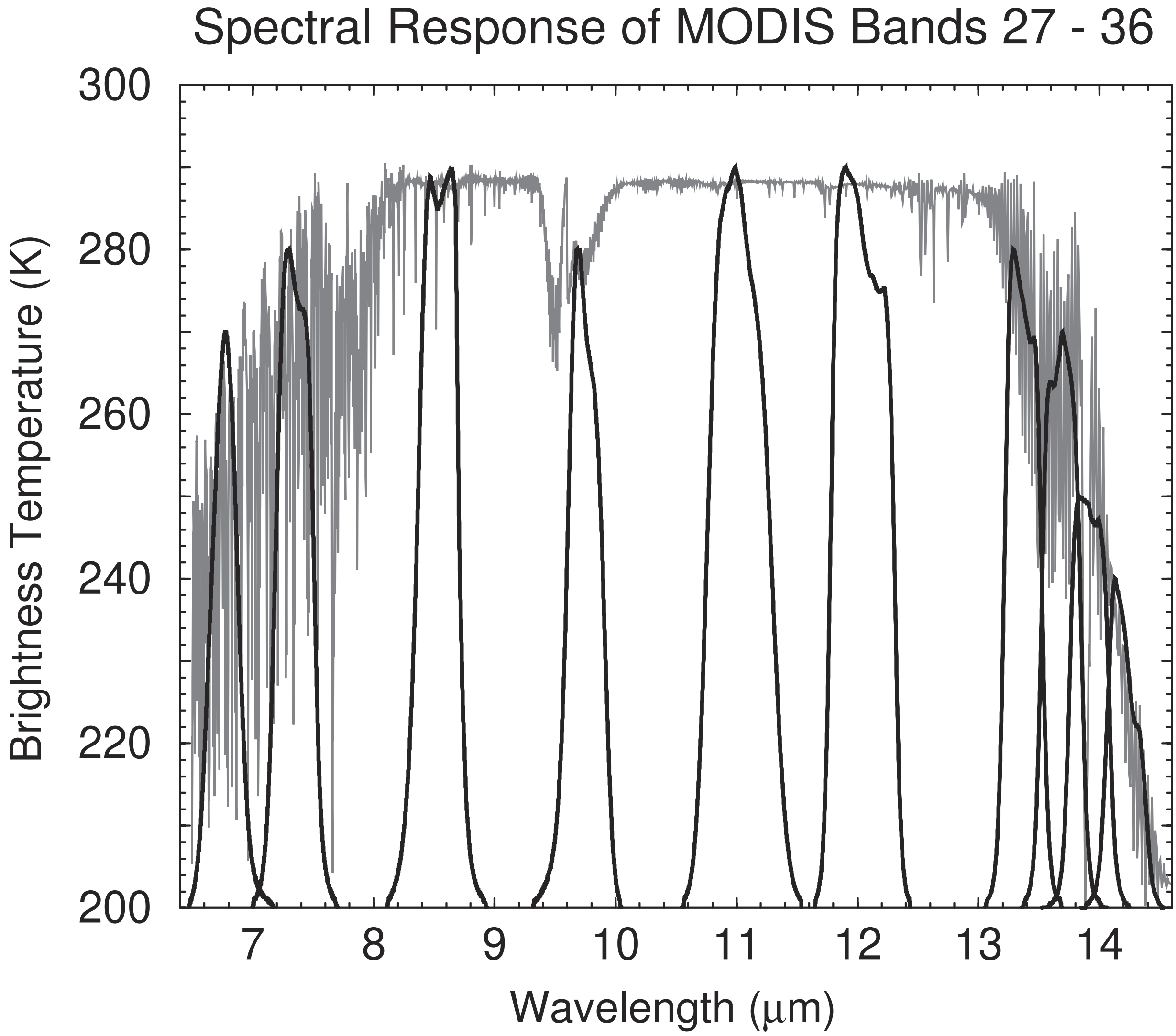

Figure 5. Averaged S-HIS brightness temperature spectra on 11 September 2000 used in the MODIS L1B assessment, with MODIS band 27–36 RSR overplotted (left to right).

dard atmosphere stratospheric profile. The resulting three altitude corrections were compared to estimate the altitude correction uncertainty (Table 2). For many bands the uncertainty is within 0.1 K. Because the MODIS L1B accuracy specification of band 30 is exceeded by its altitude correction uncertainty, no results will be presented for that band.

[15] The S-HIS radiometric accuracy is a key component of the MODIS L1B evaluation. S-HIS is calibrated in flight using two onboard high emissivity (.996, known to within 0.001) cavities with temperature knowledge to better than 0.1 K. The S-HIS in flight reference cavities have been characterized using National Institute of Standards and Technology (NIST) traceable standards. The S-HIS scene mirror is gold coated to minimize reflectance variation and polarization as a function of scan angle. The performance of S-HIS has been routinely tested in the laboratory environment to ensure ongoing high accuracy radiances from the instrument in flight. These tests include component characterization as well as system testing such as data collection over ice baths, and side by side comparisons with other interferometers. A radiometric uncertainty of the S-HIS observations was produced using the estimated uncertainty of S-HIS cavity performance (i.e., 0.1 K for cavity temperature, 0.001 for cavity emissivity) for the data collection conditions of 11 September 2000. The calculation estimates scene temperature uncertainty using a linear calibration assumption with the S-HIS blackbody cavity performance for the given flight conditions and scene temperatures. The S-HIS cavity temperatures during the 11 September data collection were 250 and 310 K. The resultant scene temperature uncertainty (Table 2) is less than 0.1 K for all window bands and 0.16 K or less for all atmospheric bands. The S-HIS uncertainty estimates are below the accuracy specification for all MODIS TIR bands. The S-HIS detectors in the 6–16 µm region are known to exhibit small nonlinear behavior. The nonlinear component of the S-HIS calibration has been estimated in the laboratory using ice bath and liquid nitrogen controlled external targets and has recently been included in the final calibration of the 11 September 2000 data set used in this evaluation; uncertainty associated with the nonlinear term of the calibration has not been rigorously evaluated

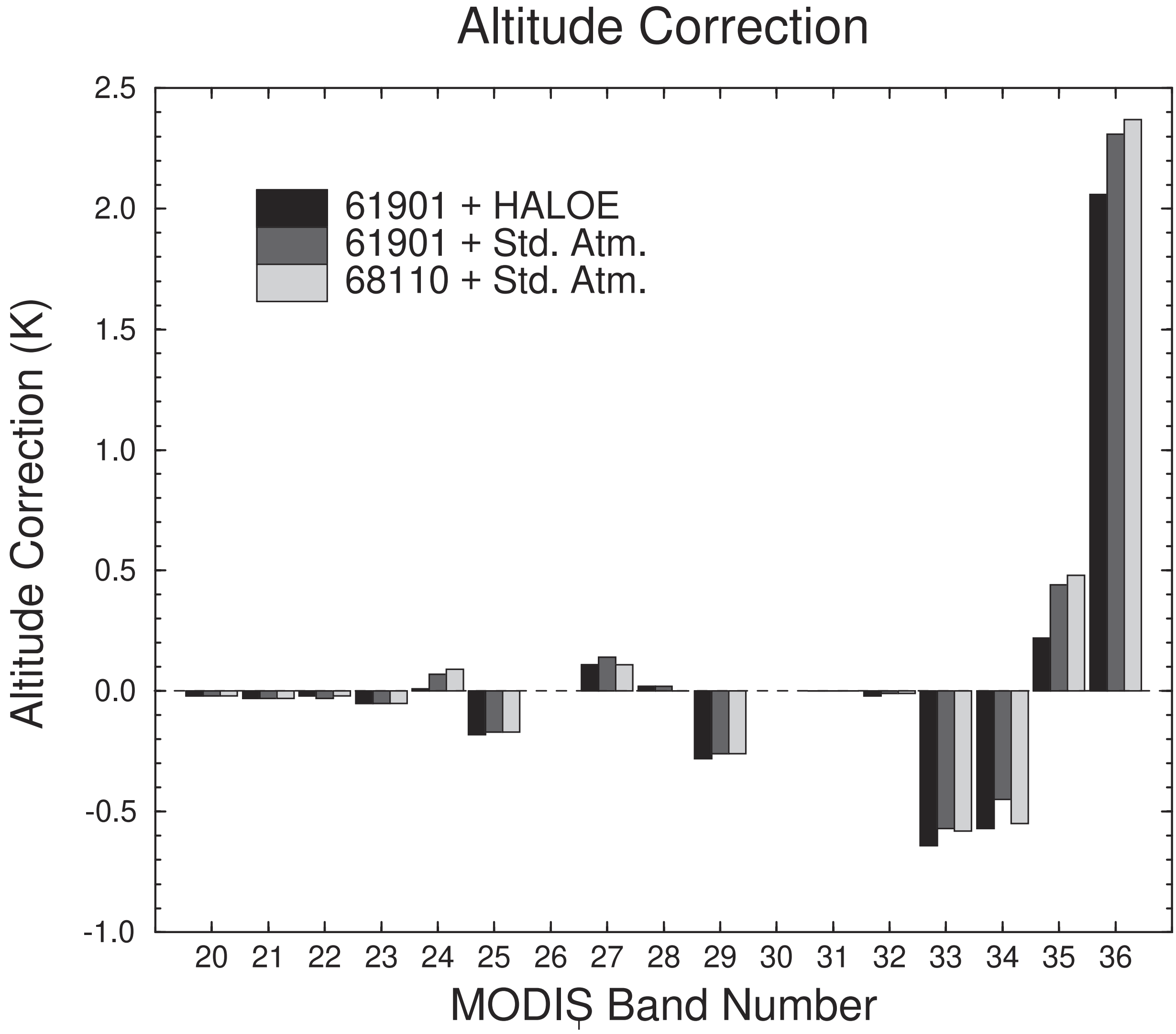

Figure 6. Altitude correction (K) to convert MODIS simulated radiances at ER-2 aircraft level (20 km) to spacecraft level (705 km). The altitude correction is based upon atmospheric characterization (radiosonde + either HALOE retrieval or standard atmosphere) used in a radiative transfer model (LBLRTM). Three atmospheric characterizations were tested and compared for 11 September 2000. The difference of the three altitude corrections suggests that the uncertainty in the altitude correction is small. The combined 61901 + HALOE characterization was chosen for application. The altitude correction is typically small for window bands. However, for CO_2 sensitive bands 33–36, it becomes large and less certain. See Table 3 for the altitude correction quantities by band. Band 30 not shown.

but has been estimated to be <0.05 K for the spectral region covering MODIS bands 27–36 (0.00 K for MODIS bands 20–25) based on the laboratory data sets. As such the nonlinear term uncertainty is expected to increase the uncertainty of Table 2 only marginally. The Root Sum of Squares (RSS) of the uncertainties listed in Table 2 show that the MODIS L1B evaluation uncertainty is within the radiometric accuracy specification for all MODIS TIR bands, except band 30.

4. Results

[16] The observed and altitude corrected simulated MODIS radiances were averaged over the selected data region of 11 September 2000 for evaluating residuals according to (1). For the simulated radiances, the MODIS RSR were linearly interpolated to the spectral resolution of S-HIS (i.e., 0.5 cm^{-1}) before the convolution. Figure 5 shows an averaged S-HIS spectra covering the LWIR spectral region for the 11 September data set with MODIS RSR overlain.

[17] As mentioned in section 2, the altitude correction used the combined 11 September 1200 UTC St. Helena Island radiosonde and the HALOE 1 September retrieval in the LBLRTM. The SST and emissivity used in the LBLRTM model were 292 K and 0.98 respectively; the SST was tuned to match the model 11 and 12 μm radiance to the S-HIS observations from the ER-2. The top of atmosphere was taken to be 100 km as there is negligible contribution above 100 km to the top of atmosphere

Table 3. MODIS Detector and Mirror Side Averaged TIR Band Residuals for 11 September 2000[a]

MODIS Band Number	Center Wavelength (μm)	Observed MODIS Average Scene Temperature (K)	Simulated MODIS Average Scene Temperature (K)	Altitude Correction (K)	Average MODIS Residual (K)	MODIS Accuracy Specification (±K)
20	3.788	291.48	290.99	−0.02	0.51	0.18
21	3.992	289.51	288.87	−0.03	**0.67**	3.00
22	3.971	289.34	289.03	−0.02	0.33	0.25
23	4.057	287.39	287.28	−0.05	**0.16**	0.25
24	4.473	257.39	256.85	0.01	0.53	0.19
25	4.545	273.55	273.69	−0.18	**0.04**	0.24
27	6.765	248.52	248.60	0.11	**−0.19**	0.27
28	7.337	268.44	268.71	0.02	**−0.29**	0.32
29	8.524	286.04	286.62	−0.28	**−0.30**	0.53
31	11.014	287.58	287.67	0.00	**−0.09**	0.34
32	12.018	287.41	287.41	−0.02	**−0.02**	0.37
33	13.361	272.30	273.08	−0.64	**−0.14**	0.61
34	13.679	261.21	260.80	−0.57	0.98	0.58
35	13.911	252.22	250.22	0.22	1.78	0.55
36	14.194	233.84	229.55	2.06	2.23	0.47

[a]The residual of each band is the difference between the average of 287 MODIS observations and 869 MODIS simulations (using S-HIS data) in the common data region. Band 30 not provided due to uncertainty in ozone profile. Band 26 is a reflectance band. Residuals that are within the prelaunch accuracy specification are shown in bold.

radiance for MODIS TIR bands. The RSR of channel 5 of each band was deemed representative of the average RSR of all detectors in the model calculation. Testing suggested that using each detector independently and later averaging had negligible impact on the final L1B accuracy assessment.

[18] Figure 6 and Table 3 show the altitude correction is small for MODIS window bands and only becomes important for bands that are strongly influenced by upper tropospheric and stratospheric absorption (i.e., occurring above the ER-2 level). The combined radiosonde–HALOE retrieval accuracy in characterizing the atmosphere on 11 September 2000 is not validated; however, testing the two additional atmospheric characterizations shown in Figure 3 suggests that the altitude correction uncertainty is equal to or less than 0.31 K for all bands except band 30. Nevertheless, large altitude corrections for bands 33–36 reduce confidence in their L1B residuals.

[19] The L1B residuals, in brightness temperature units, are shown in Figure 7 and listed in Table 3. The MODIS LWIR split window (bands 31 and 32) combination residuals are near zero and within the prelaunch specification for the nadir views of 11 September. These bands are used extensively in a number of MODIS products, including SST, LST, atmospheric temperature/moisture profiles, and cloud top properties, among others. Also, bands 31 and 32 exhibit very similar residuals, suggesting that the split window difference is also very accurate. The scene temperature of these bands on 11 September is close to the nominal MODIS onboard blackbody operating temperature (290 K). The MWIR window band (20, 22, and 23) residuals are also very near or within specification. Undocumented Sun glint in the data region may be influencing the MWIR band residuals by causing a scene temperature increase over the 7–18 min between the ER-2 and MODIS data collection. The scene temperature change over this short duration in the data region is expected to be small (<1 K) but difficult to quantify as it is a function of sea state and the time difference between S-HIS and MODIS. Of interest, the MWIR residuals suggest that known electrical cross talk in MODIS shortwave IR (SWIR) reflectance bands 5, 6, 7, and 26 (1.24, 1.6, 2.1, and 1.38 μm, respectively) and MWIR bands has only modest impact on the MWIR band residuals for the flat thermal, low reflectance data scenes used in this analysis. This may be a benefit of the low, uniform signal of the ocean surface in the SWIR reflectance bands.

[20] MODIS bands 27 and 28 (6.7 and 7.3 μm midtropospheric water vapor bands) residuals are within specification. These bands are both affected by detector striping (not shown) which is included in the averaged residual of Figure 7. Band 29 (8.5 μm, low level water vapor) is also within specification in this evaluation. The nonlinear component of the S-HIS calibration in this spectral region has recently been reevaluated. Early MODIS band 29 residuals [*Moeller et al.*, 2001] based on S-HIS comparisons now appear to have overestimated the residual of band 29. Additionally, *Wan et al.* [2002] have found this band to be within specification using ground-based observations in a dry atmosphere environment. However, the calibration of band 29 (and other LWIR bands) should continue to be monitored as the MODIS scene mirror exhibits reflectance and polarization sensitivity for band 29 to the angle of incident radiance [*Barnes et al.*, 1998].

[21] The LWIR CO_2 sensitive bands 33–36 exhibit a pattern of increasingly positive residual with wavelength and appear to be out of specification for bands 34–36. These bands are affected by a known optical cross talk from the 11 μm region, with an uncorrected impact of 3 K or more on clear scene calibrated brightness temperatures of bands 35 and 36; however, a correction for this influence is applied in the MODIS L1B processing algorithm. Typical scene temperatures in bands 34–36 are 30–70 K below the MODIS 290 K onboard blackbody operating temperature, increasing the potential impact of any calibration slope error. The altitude correction applied in the analysis must also be considered as a possible source of the large residuals in these bands. Since the characterization of the atmosphere is not validated, it may include undocumented error, especially for band 36 whose altitude correction is large. This issue and the systematic behavior of the band 33–36 residuals raise questions on the evaluation for these bands. It is noteworthy however

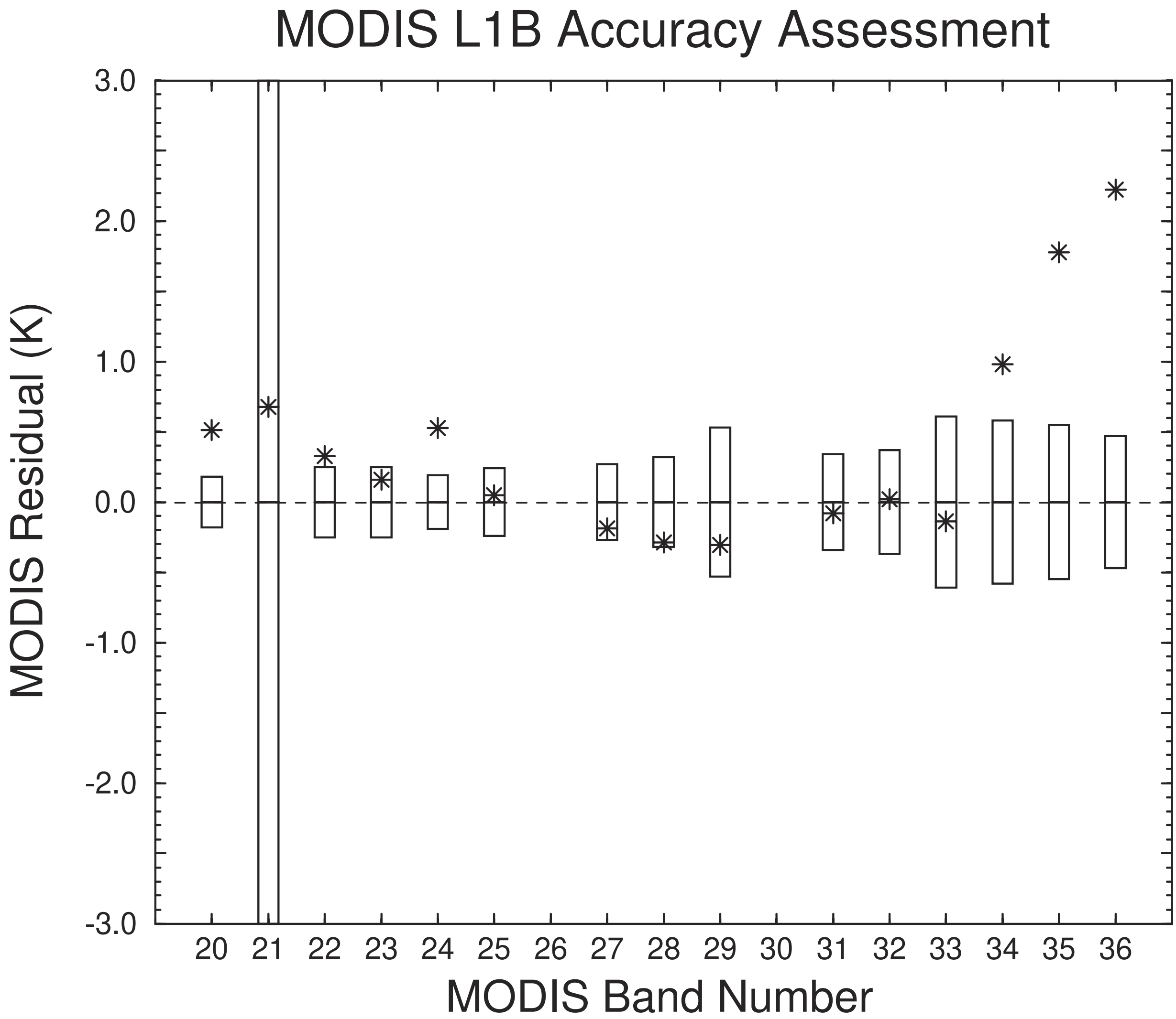

Figure 7. MODIS TIR band average residuals (star symbols) with prelaunch accuracy specification envelope for each band defined by the vertical boxes. See Table 3 for numbers. MODIS band 30 is not shown. Most MODIS bands show residuals on this day of less than 0.5 K, within or near the MODIS specification. The upper tropospheric CO_2 bands 34–36 (13.68, 13.91, and 14.19 μm, respectively) have large residuals; these bands may be influenced by undocumented uncertainty in the altitude correction. The residuals of the MWIR bands 20–23 (3.79–4.06 μm) may be influenced by undocumented Sun glint present in the data scenes (S-HIS data collection preceded MODIS data collection by 7–18 min).

that these residuals are similar to preliminary residuals obtained by *Moeller et al.* [2001] from the ER-2 activity called TX-2001, using MAS and S-HIS data from an 1 April 2001 underflight of MODIS over the Gulf of Mexico.

5. Summary and Conclusions

[22] This paper takes a first look at Collect 3 (V3.0.0.6) MODIS L1B TIR band radiance accuracy using data from the SAFARI 2000 field campaign. The first look was a search for unexpected performance by MODIS early in its lifetime. The averaged (over all detectors and both scene mirror sides) residuals of each band, while of interest, should not be considered as recommended bias corrections of the MODIS data set. To produce such numbers requires a careful characterization of surface and atmospheric conditions, and should evaluate detector and scene mirror side dependent residuals over a range of scence temperatures. The evaluation however remains meaningful in a broader sense by finding that the average residual of most bands is very near or within specification, in the context of the estimated uncertainties in this analysis. There does not appear to be a significant influence by electronic cross talk on the MWIR bands 20–25 for the flat thermal scenes of the analysis. LWIR split window band 31 and 32 residuals are very low, raising confidence in their calibration. Mid tropospheric water vapor band 27 and 28 residuals are also within specification, despite known detector striping in these bands. Larger average residuals in the LWIR upper tropospheric CO_2 bands are not considered strong indications of L1B performance issues due to possible undetected uncertainty in the altitude correction used in the analysis.

[23] Other ER-2 campaigns (e.g., TX-2001, CLAMS, and plans for TX-2002) have collected or will collect MAS and S-HIS data sets useful for assessing MODIS L1B accuracy. These will be rigorously evaluated in the future to provide further insight on MODIS L1B TIR band calibration. Additionally, the recent launch (May 2002) of the NASA Aqua satellite provides a second MODIS instrument on orbit. Performance issues of MODIS on Terra (e.g., optical cross talk into bands 33–36, electronic cross talk in SWIR/MWIR, etc.) were largely mitigated during the buildup of MODIS for Aqua. Comparisons between MODIS on Terra and Aqua may reveal residual impact of these influences in the MODIS Terra L1B product.

[24] **Acknowledgments.** This research has been supported by the EOS Science Project Office under NASA contract NAS5-31367. We would like to extend our thanks to the MODIS Characterization Support Team (MCST) at GSFC for their support in obtaining Collect 3 MODIS L1B data and for sharing their knowledge of MODIS instrument performance. We also wish to thank the S-HIS team at the University of Wisconsin for providing the S-HIS data and the Airborne Sensor Facility Group at Ames Research Center for providing the MAS data. The authors would like to thank the Upper Atmosphere Research Satellite (UARS) Project (Code 916) and the Distributed Active Archive Center (Code 902) at the Goddard Space Flight Center, Greenbelt, MD 20771 for the production and distribution of HALOE data, respectively. These activities are sponsored by NASA Earth Science Enterprise.

References

Barnes, W. L., T. S. Pagano, and V. V. Salomonson, Prelaunch characteristics of the Moderate Resolution Imaging Spectroradiometer (MODIS) on EOS-AM1, *IEEE Trans. Geosci. Remote Sens.*, *36*(4), 1088–1100, 1998.

Clough, S. A., and M. J. Iacono, Line-by-line calculations of atmospheric fluxes and cooling rates, 2, Applications to carbon dioxide, ozone, methane, nitrous oxide and the halocarbons, *J. Geophys. Res.*, *100*, 16,519–16,535, 1995.

Godden, G., MODIS (MCST) Thermal Emissive Band Workshop, Miami, FL, Section 10 Review of B31 Leaks into Bands 32–36, February 4 –5, 1999.

Guenther, B., G. D. Godden, X. Xiong, E. J. Knight, S.-Y. Qiu, H. H. Montgomery, M. M. Hopkins, M. G. Khayat, and Z. Hao, Prelaunch algorithm and data format for the Level 1 calibration products for the EOS-AM-1 Moderate Resolution Imaging Spectroradiometer (MODIS), *IEEE Trans. Geosci. Remote Sens.*, *36*(4), 1142–1151, 1998.

King, M. D., et al., Airborne scanning spectrometer for remote sensing of cloud, aerosol, water vapor, and surface properties, *J. Atmos. Oceanic Technol.*, *13*, 777–794, 1996.

King, M. D., S. Platnick, C. C. Moeller, H. E. Revercomb, and D. A. Chu, Remote sensing of smoke, land and clouds from the NASA ER-2 during SAFARI 2000, *J. Geophys. Res.*, *108*, doi:10.1029/2002JD002307, in press, 2003.

McGill, M. J., D. L. Hlavka, W. D. Hart, V. S. Scott, J. D. Spinhirne, and B. Schmid, The Cloud Physics Lidar: Instrument description and initial measurement results, *Appl. Opt.*, in press, 2002.

Moeller, C. C., D. D. LaPorte, H. E. Revercomb, and W. P. Menzel, Radiometric evaluation of MODIS emissive bands through comparison to ER-2 based MAS data, Earth Observing Systems VI, 1–3 August 2001, *SPIE Proc.*, *4483*, 211–221, 2001.

Revercomb, H. E., et al., Recent results from two new aircraft-based Fourier transform interferometers: The Scanning High-Resolution Interferometer Sounder and the NPOESS Atmospheric Sounder Testbed Interferometer, paper presented at the 8th International Workshop on Atmospheric Science from Space Using Fourier Transform Spectrometry (ASSFTS), Toulouse, France, 16–18 November 1998.

Russell, J. M., III, L. L. Gordley, L. E. Deaver, R. E. Thompson, and J. H. Park, An overview of the Halogen Occultation Experiment (HALOE) and preliminary results, *Adv. Space Res.*, *14*, 9–13, 1994.

Wan, Z., Y. Zhang, Z.-L. Li, R. Wang, V. V. Salomonson, A. Yves, R. Bosseno, and J. F. Hanocq, Preliminary estimate of calibration of the moderate resolution imaging spectroradiometer thermal infrared data using Lake Titicaca, *Remote Sens. Environ.*, *80*, 497–515, 2002.

S. A. Ackerman and C. C. Moeller, Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin-Madison, 1225 West Dayton Street, Madison, WI 53706-1695, USA. (chris.moeller@ssec.wisc.edu)

R. O. Knuteson and H. E. Revercomb, Space Science and Engineering Center, University of Wisconsin-Madison, Madison, WI 53706-1695, USA.

W. P. Menzel, National Oceanic and Atmospheric Administration (NOAA)/National Environmental Satellite Data and Information Service (NESDIS)/ORA, Madison, WI 53706-1695, USA.